Inverse Problems in Hydrologic Radiative Transfer

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LONG-TERM GOALS

The long-term scientific goal of my research is to better understand the distribution of phytoplankton in the world's oceans through remote sensing their influence on the optical properties of the water.

OBJECTIVES

Optically, phytoplankton reveal their presence through their influence on the inherent optical properties (IOP's) of the water. The main effect of phytoplankton is to increase the absorption of light by virtue of the strong absorption by their photosynthetic (chlorophyll a) and accessory pigments. A secondary effect is to increase the backscattering coefficient of the medium in a manner that depends on the concentration of pigments. Although techniques for measuring the absorption coefficient directly (e.g., in-situ AC9 measurements or in-vitro filterpad absorption) are becoming accepted by the scientific community, laboratory techniques for measuring backscattering are tedious and subject to error, and in-situ techniques for backscattering are in their infancy. In addition, in most in-situ measurements the volume of medium that is sampled is small and may not be representative of the whole water body, even in a homogeneous medium. Thus, in the past, there has been considerable effort devoted toward indirectly inferring these IOP's by virtue of their affect on the apparent optical properties (AOP's), e.g., the diffuse reflectance of the water (the color of the water) or the downwelling irradiance attenuation coefficient. These AOP's are perhaps the most frequently measured quantities in hydrologic optics. Clearly, interpretation of such observations requires a detailed understanding of the influence of phytoplankton on the IOP's, and their link to the AOP's.

The IOP $\leftrightarrow$ AOP link forms the focus of the present research. In particular, our research is centered on deriving the IOP's from measurements of the AOP's. This is an example of the inverse problem of radiative transfer. It is important in that IOP's determined from AOP's are, by definition, sampled at a scale appropriate for radiative transfer, and for remote sensing. Also, the retrieved IOP's possess the attribute that when combined with the radiative transfer equation, they reproduce the measured AOP's. In the present research, we focused on developing methods for deriving the vertical profiles of the absorption and backscattering coefficients from measurements of the vertical profiles of downwelling irradiance and either upwelling radiance or upwelling

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irradiance in the absence of inelastic processes. As the presence of inelastic processes can make a significant contribution to the in-water light field, a study, aimed at including the influence of inelastic processes in the inversion algorithm and deriving the parameters describing the inelastic processes, has been initiated.

APPROACH

Our approach for a *vertically stratified* medium is to use the basic algorithm developed by Gordon and Boynton (1997) to retrieve the absorption and backscattering coefficients of a *homogeneous* water body. Briefly, given the measured AOP's, we use trial IOP's to solve the radiative transfer equation (RTE) thereby generating trial AOP's, which are then compared to the measurements. Based on the error in the trial AOP's, we vary the trial IOP's in a manner as to produce better agreement between the trial and the measured AOP's. This is carried out in an iterative fashion with the RTE solved using the new trial IOP's at each step in the iteration. The resulting profiles of the absorption and backscattering coefficients have the attribute that they yield AOP's that agree with the measurements. Since inelastic processes (Raman scattering and/or solar-induced fluorescence) can seriously degrade the performance of the algorithm particularly in the red, by causing it to retrieve incorrect profiles of both absorption and backscattering, we augmented our study to include the affects of inelastic processes. This will be effected first for Raman scattering because the Raman scattering cross sections are well known. The plan is to use estimates or measurements of the AOP's at the excitation wavelength to estimate the Raman contribution at the wavelength of interest. The existing algorithm will then be applied to the elastic component of the light field to find trial IOP's, whch in turn will be used to generate a new estimate of the Raman component, i.e., we will nest our elastic inversion algorithm within a routine that provides the Raman contribution

WORK COMPLETED

We developed an algorithm for retrieving vertical profiles of the absorption and backscattering coefficients for a vertically stratified ocean by measuring the vertical profiles of the AOP's, the downwelling irradiance, and the upwelling radiance or irradiance. Details of the extensive testing are provided in Gordon and Boynton (1998). In testing the algorithm using field data in collaboration with J. Mueller and J.R.V. Zaneveld, we found that, as expected, inelastic processes (Raman scattering and/or solar-induced fluorescence) seriously degraded the performance of the algorithm. Thus, we augmented our objective to include the affects of inelastic processes, and ultimately to derive the parameters describing the inelastic processes. To this end, we have completed the first phase of development of an elastic-inelastic inversion algorithm: we have wrapped the code to compute the Raman contribution around the elastic inversion code. Initial testing is underway and will be reported during Ocean Optics XIV.

As part of our Raman work, we have also reexamined the contribution of Raman scattering to the water-leaving radiance, the ocean-color remote-sensing signal. This work has been submitted for publication in *Applied Optics* (Gordon, 1998).

RESULTS

The results of tests of our latest algorithm for inverting downwelling irradiance and either upwelling radiance or upwelling irradiance profiles to retrieve profiles of the absorption and backscattering coefficients is provided in Gordon and Boynton (1998). The significant results are: (1) the algorithm does not require knowledge of the scattering phase function of the medium; however, we have found that the results for the backscattering coefficient are better the closer the phase function assumed in the algorithm is to the true phase function; (2) excellent retrievals of the absorption coefficient can be obtained with a very inaccurate phase function; (3) when the spacing between the AOP data samples is sufficiently small that the derivatives of the irradiances (the *K*'s) can be accurately computed, the simulations suggest that the algorithm is capable determining the vertical structure of a stratified water body, and usually provides the absorption coefficient profile with an error less than about 2% and the backscattering coefficient profile with an error less than about 10% in the absence of inelastic scattering; and (4) the error in the retrieved absorption coefficient is approximately equal to the error in determining the downwelling irradiance attenuation coefficient from the downwelling irradiance data. In tests with field data provided by J. Mueller and J.R.V. Zaneveld, the algorithm retrieved values of $a(z)$ at 488 nm that typically agreed with AC9 measurements to better than 0.01 m^{-1} at depth, and ± 0.015 m^{-1} near the surface. The correct vertical profile was also retrieved.

Testing of the new inversion algorithm including inelastic processs has only just started. Although encouraging, there are no concrete results at this time.

Our reexamination of the influence of Raman scattering on water-leaving radiance (relevant to remote sensing of ocean color) was prompted by results in Waters (1995) that seemed to contradict computations provided by Ge, Gordon, and Voss (1993). We limited our study to Case 1 waters and carried out radiative transfer simulations that combined the latest reported measurements of the absorption coefficient of pure water (Pope and Fry, 1997) with direct measurements of the spectral variation of the Raman scattering coefficient (Bartlett *et al*., 1998). The resulting contribution of Raman scattering was then compared to experimental measurements of the water-leaving radiance and the fractional contribution of radiance produced by Raman scattering to the total radiance measured at a given wavelength was determined. The results show that (1) the contribution of Raman scattering to the water-leaving radiance in an ocean of pure sea water is as much as 50-100% larger than earlier predictions, and (2) the Raman contribution does not decay as rapidly with increasing concentrations of chlorophyllous-like pigments (C) as predicted earlier. In fact, the Raman fraction for $C \leq 1$ mg/m^3 is > approximately 8% at wavelengths of interest in ocean color remote sensing, and therefore cannot be ignored in ocean color modeling.

IMPACT/APPLICATIONS

Development of a method for inverting irradiance profiles to obtain the IOP's in vertically stratified waters is a significant accomplishment. We believe that the algorithm will be of significant utility for processing existing and future experimental irradiance profile data to estimate the absorption and backscattering coefficients, and their relationship to constituent concentrations, for use in ocean color remote sensing algorithms. Furthermore, the algorithm provides IOP's that are, by definition, sampled at a scale appropriate for radiative transfer, and therefore, will be of

significant value for examining questions of closure concerning traditional IOP-instruments that sample at scales of a few cubic centimeters.

TRANSITIONS

We were in the process of preparing a package inversion software in a “user friendly” form for use by others. This has been suspended until the Raman portion is integrated. Presently, to our knowledge, no one is using this inversion algorithm.

RELATED PROJECTS

We are working with J. Mueller and J.R.V. Zaneveld to compare our estimates of absorption and backscattering profiles from downwelling irradiance and upwelling radiance with direct measurements using in-situ instrumentation. We expect this work will contribute to AOP-IOP closure. Their work in this area is funded by NASA. We are developing a bi-directional model of the water-leaving radiance (including Raman contributions) for Case 1 waters. This will be used in processing MODIS imagery, and is funded by NASA.

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